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Integrated collector storage solar water heaters

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Abstract

The Integrated Collector Storage Solar Water Heater (ICSSWH) developed from early systems comprised simply of a simple black tank placed in the sun. The ICSSWH, by its combined collection and storage function suffers substantial heat losses to ambient, especially at night-time and non-collection periods. To be viable economically, the system has evolved to incorporate new and novel methods of maximising solar radiation collection whilst minimising thermal loss. Advances in ICS vessel design have included glazing system, methods of insulation, reflector configurations, use of evacuation, internal and external baffles and phase change materials.

Keywords: Optical efficiency; ICSSWH; Thermal performance; Technological development

Contents

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1. History of the integrated collector storage solar water heater

The first ICSSWH systems were exposed tanks of water left out to warm in the sun on a few farms and ranches in the Southwest of the USA in the late 1800s. They reportedly produced sufficient hot water for showering by the late afternoon on clear days [1]. The first solar water heater, manufactured commercially under the trade name 'The Climax Solar-Water Heater', was an ICSSWH patented in 1891 [2]. A diagram of Kemp's design is shown in Fig. 1. This water heater could be used from April to October in the state of Maryland in the eastern USA, producing water hotter than 38 °C on sunny days, it was claimed even during early spring and in late autumn when daytime temperatures sometimes approached freezing. The unit was simply four small (29 l) heavy galvanised iron cylindrical vessels, painted a dull black and mounted in a wooden box insulated with felt paper, under a single-glazed aperture. An advertisement for the Climax Solar-Water Heater is shown in Fig. 2. Its purchase price in 1892 was $15, equivalent to $302 (based on the Consumer Price Index) today. The manufacturing rights were sold to two southern Californian businessmen in 1895. With a favourable climate and high prices of 'conventional' fuels, the Climax water heater found markets in both California and neighbouring Arizona. One thousand and six hundred units were sold in southern California alone within 5 years [1]. A dozen ICSSWH patents were filed in the USA up until 1911 but only a few of the designs proved to be successful commercially.

Early inventors and entrepreneurs did not study ICSSWH system performance systematically. In 1936, Brooks at the University of California Agricultural Experimental Station, USA [3], carried out the first detailed study of closed and exposed, single and multiple ICS tank systems. However, the discovery of natural gas and oil fields together with the promotion and effective subsidy of those energy sources, discouraged serious investigation of ICSSWH units in the USA and efforts ceased until the early 1970s.

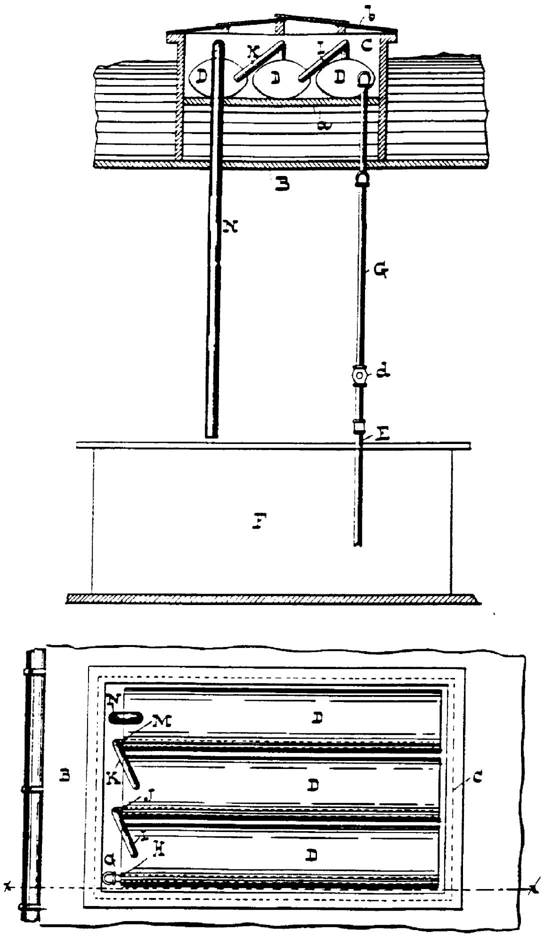

Fig. 1. Diagram from Kemp's patent for the climax solar-water heater [2].

This was not, however, the case in Japan, where a suitable climate, high consumption of hot water combined with a lack of fossil fuels and hence high-energy costs, stimulated the development of solar water heating. Though several Japanese patents were issued for solar water heaters during the early part of this century, it was not until the 1940s that commercial development of ICSSWH systems in Japan began. The initiation of commercialisation has been attributed to Yamamoto [1] who, when visiting a rural area, noticed a large bath tub full of water covered by a sheet of glass left out in the sun all day. In 1947, Yamamoto had designed Japan's first commercial solar energy water heater. In the late 1950s, the 'closed-pipe' ICSSWH system on which many modern Japanese units are based was introduced [4]. Fig. 3 illustrates the design of a stainless steel pipe type solar water heater. Also pioneered in Japan in the 1950s was the closed membrane or plastic bag ICSSWH, sometimes referred to as the 'plastic pillow' type. This large rectangular Polyvinylchloride bag, usually with the bottom surface a black membrane and the top

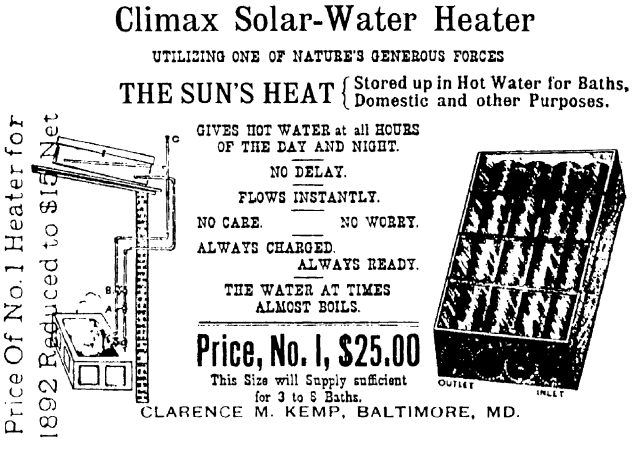

Fig. 2. Advertisement for the climax solar water heater, 1892 [1].

membrane transparent, proved to be a popular commercial product in Japan, with a peak of approximately 240,000 units sold in 1963–64 [5].

After November 1973, there was global concern for alternative energy sources to replace OPEC-embargoed Arabian oil. This caused a renewed, world-wide interest in solar energy, and in the USA, South Africa, Australia and Japan a modest revitalisation of interest in the ICSSWH. Most of this work was undertaken by individual passive solar enthusiasts, joined subsequently by universities and other research institutions. More recently, following global initiatives to promote renewable energy technologies to curb greenhouse gas emissions, there has been renewed interest in solar water heating and ICSSWHs.

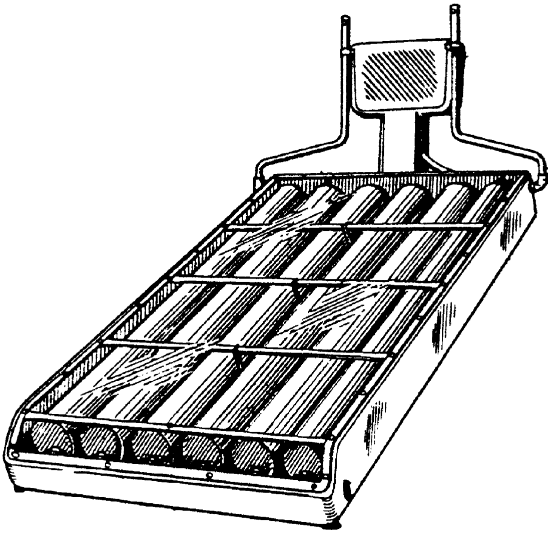

Fig. 3. The stainless steel pipe type solar water heater [5].

2. Technologial development of the ICSSWH

The heat transfer processes in an ICSSWH are shown in Fig. 4. Development of the ICSSWH has sought to enhance collection of insolation and reduce heat losses. Early systems comprised of simple exposed tanks of water left out to warm in the sun suffered substantially from heat losses to ambient, especially at night-time and during non-collection periods. Unless the heated water was withdrawn fully at the end of the collection period, losses to ambient usually led to only luke-warm water being available early the next day. This reduced the overall solar fraction rendering the unit less viable economically. Indeed this deficiency led to the prominence of thermosyphon solar water heaters with diurnal heat storage in the late 19th century displacing ICSSWH systems [6]. To overcome excessive heat loss and be in a position to compete with solar water heater systems with separate collectors and stores, ICSSWH designs have evolved to incorporate new and novel methods of improving performance.

2.1. Vessel design

The vessel containing the heated water is the central component in an ICSSWH. Its primary function is to absorb solar radiation and transfer the thermal energy to its interior.

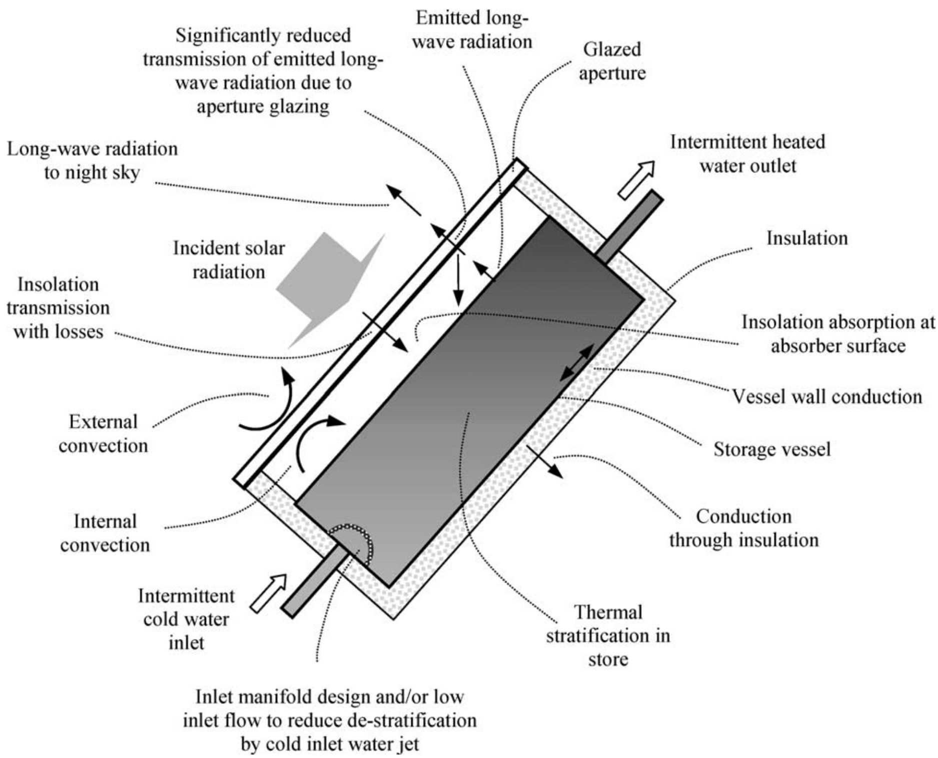

Fig. 4. ICSSWH heat transfer mechanisms summarised.

The orientation, size and shape of the vessel, along with vessel materials and coatings affect the amount of radiation absorbed.

2.1.1. Vessel size and shape

The size and shape of the vessel has a significant effect on the collection of solar radiation. The greater the exposed surface area to volume ratio the less time will be required for insolation to heat up the water store. For example, for a shallow rectangular vessel with a high surface area/volume ratio, the incident insolation has a small depth of water to heat up. However, a store with a large exposed surface area will also lose substantial amounts of heat by convection and long-wave radiation during normal conditions and will cool down significantly by radiative losses to the night sky.

The first commercial ICSSWH unit [2] had four oval-shaped cylindrical vessels (29 l each) with the flattened surface facing the sun. This particular shape of tank increased the surface area exposed to the sun. The importance of the surface area/volume ratio was realised by Haskell in 1907 [7] who patented an 'improved' ICSSWH design that used a shallow rectangular tank having an inherently higher surface area to volume ratio than cylindrical vessels. This design yielded a successful product with a more rapid warm-up in the morning and hotter water on partially cloudy days. Japanese research in the 1940s concentrated on rectangular tanks in open-type collectors (Fig. 5) and cylindrical vessels. The latter developed into long thin closed-pipes (Fig. 6). Both systems had small surface area to volume ratios when compared to designs from the USA. Subsequent work in Japan, in the 1970s, stayed with this proven concept. Coiled galvanised pipes have also been employed as ICSSWH vessels [8].

The commercial market today is dominated by systems based on cylindrical vessels that are cheaper, pressure resistant and available readily. The modern CopperSun multiple cylindrical vessel ICSSWH is shown in Fig. 7. Significant studies have been conducted to

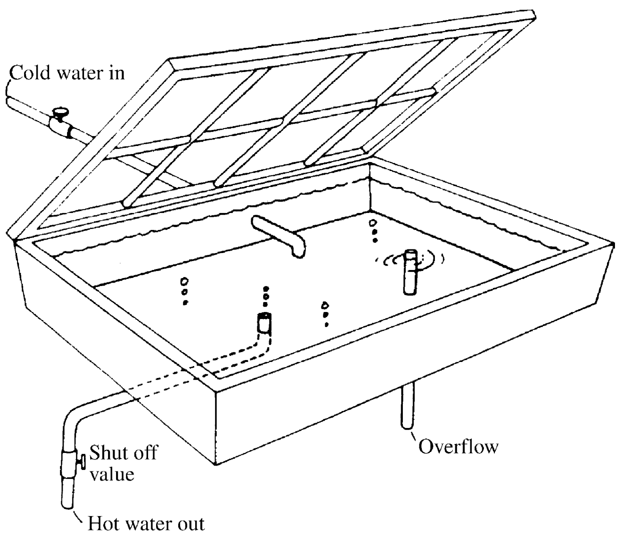

Fig. 5. Japan's first commercial solar water heater, invented by Yamamoto in 1947 [1].

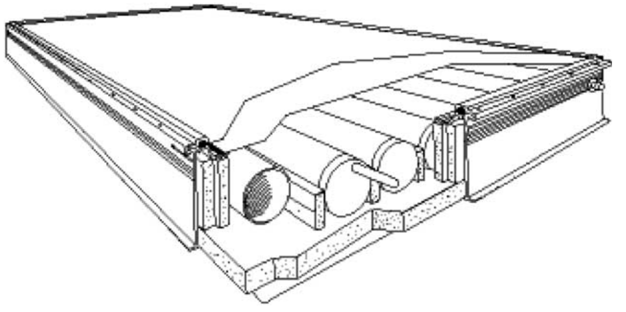

Fig. 6. Multi-vessel ICS unit with cylindrical tanks [117].

advance the understanding and development of cylindrical ICS vessels and their use in ICSSWHs [3,9–31].

The aspect ratio is an important factor in system performance. For a cylindrical vessel with a fixed length, the diameter decreases as the aspect ratio increases and so does the total surface area to volume ratio, leading to greater heat loss from the vessel. As the aspect ratio increases, so does the tendency of the water in the vessel to stratify thermally when the vessel is mounted vertically along the N–S axis, which means that long-thin vessels are more suitable than short-squat ones [32]. Due to practical constraints and financial restrictions, a compromise must be reached between a high aspect ratio, for greater thermal stratification, heat gains and heat losses due to area/volume ratio and construction costs.

Studies have shown that rectangular vessels can operate and perform as well as cylindrical vessels in ICSSWHs [10,33–43].

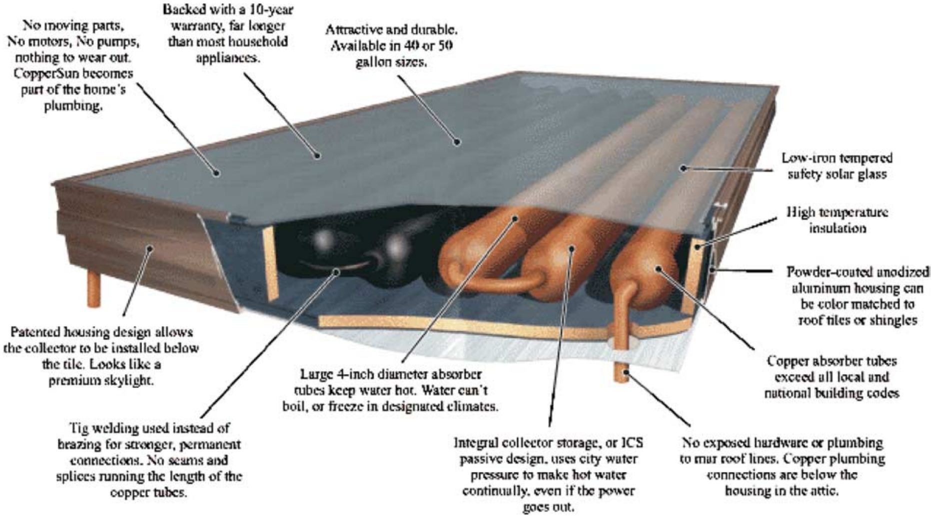

Fig. 7. Market attribute of the 'CopperSun' multiple cylindrical vessel ICSSWH (Reproduced by permission from Sun Systems, Inc.).

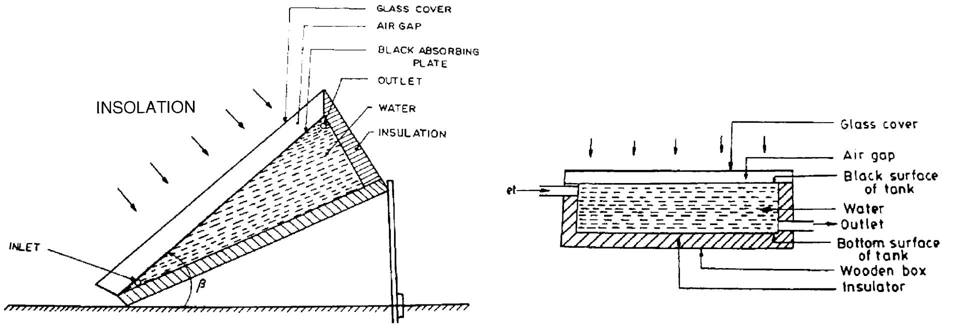

Fig. 8. Schematic detail of rectangular and triangular built-in-storage solar water heaters [47].

Several previous studies have suggested that ICSSWHs with a triangular design [44–47] have better solar collection and exhibit better heat transfer between the absorbing surface and stored water due to increased natural convection. The systems studied by Kaushik et al. [47] are shown in Fig. 8. A comparative study conducted by Soponronnarit et al. [48] evaluated experimentally two ICSSWH systems side by side under identical operating conditions. One unit was rectangular in design and the other triangular. Both units had an absorbing area of 0.7 m^2 and capacity of 75 l. The triangular and rectangular vessels had thermal efficiencies of 63 and 59%, respectively. Heat loss over non-collecting periods was less for the triangular vessel. Sokolov and Vaxman [49] first suggested the use of a triangular integral compact solar water heater using a baffle plate to separate the absorbing surface and storage volume. Water circulation was thermosyphonic. In their work and subsequent studies by Vaxman and Sokolov [50], they showed an efficiency of 53% for such a triangular system.

Abdel-Rehim [51] presented a novel ICS vessel design based on a pyramid shape. The total surface area of the collector is about of 1.68 m^2 and the capacity of the water storage tank is about 150 l. The results showed that the proposed solar water heater provided about 175 l/day of hot water of at an average temperature range of 40–60 °C in the Egyptian climate.

'Plastic pillow' ICSSWHs have been developed in a wide variety of forms [52]. The water pillow is formed by heat sealing black polyethylene or Tedlar layers [53] to form 'pillow-like' formations, some of which include aluminium mylar reflector systems, may be covered at night with insulation [54]. Very large area water pillow systems were developed in the mid-1970s at the Lawrence Livermore Laboratory in California, USA [55–57]. Water pillow arrays called 'shallow solar ponds' (not to be confused with non-convecting salt gradient solar ponds) were formed by combining 3.5 m wide by 60 m long modules. They were intended as an effective way to produce large-scale electric power from solar energy. Stored hot water heats a thermodynamic fluid (Freon 11) which drives a turbine and an electric generator. Another suggestion is the potential use of shallow solar ponds to provide process hot water, up to the boiling point, for industrial and commercial purposes.

In an experimental and theoretical investigation on a plastic pillow type solar water heater made of PVC [58], a transient heat transfer model was developed to investigate performance. Under various climatic conditions the model showed good agreement with experimental results. A further study was conducted by Sodha et al. [59] into plastic bag solar water heaters. The capacity of the system was reported to be 100 l and it used two transparent foils separated by a honeycomb structure. Bansal et al. (1987) [118], reported on the thermal performance of shallow solar pond water heaters tested in Juelich, Germany, compared with the performance of a conventional distributed solar water heater at the same location. Fig. 9 details the integrated collection and storage plastic 'pillow' type solar water heater fabricated from fluorinated plastics. The border refers to the welded seam edge bonding the pillow layers together. Both solar water heating systems were reported to have similar thermal efficiencies, although after 8.00 p.m. the heat loss from the 'pillow' type system was significantly greater than the distributed system.

2.1.2. Configuration and interconnection of vessels

The number, interconnection and mounting of vessels has a significant effect upon performance. Regardless of the vessel mounting position, horizontally or vertically, the inlet and outlet are always arranged so that hot water is withdrawn from the top and cold water replenished at the base to minimise mixing of hot and cold water. In many cases, dividing water storage over two or more vessels improves stratification within each vessel as cold inlet water entering the lowest tank is prevented from mixing with the hottest water in the final tank. The first patented ICSSWH design [2] used multiple horizontal vessels linked in series. Cold water entered the first tank at low level whereupon the outlet exited at high level to fed the next tank at low level with the eventual hot water being drawn off at high level from the third tank in series. Stacking each receiving tank at a higher level facilitated thermal stratification between the vessels.

More recently, studies by Tripanagnostopoulos et al. [27] have evaluated the performance of double vessel systems. Two differing ICS systems utilising asymmetric CPC reflectors were investigated experimentally. Fig. 10 illustrates the system design. The system with both tanks fully exposed exhibited a better collection efficiency over the partially exposed design, although the latter had improved heat retention during non-collection periods over the fully exposed design. In addition, there is a significant

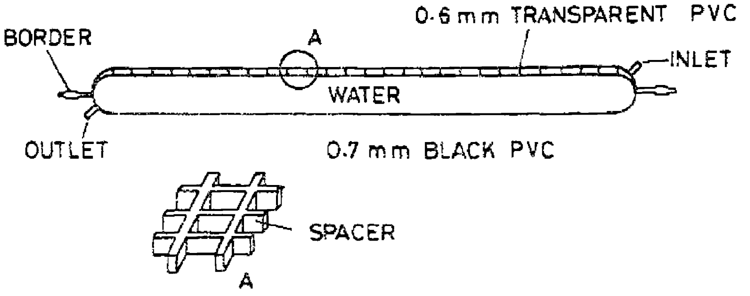

Fig. 9. Schematic detail of an integrated collection and storage plastic 'pillow' type solar water heater (Bansal et al., 1987).

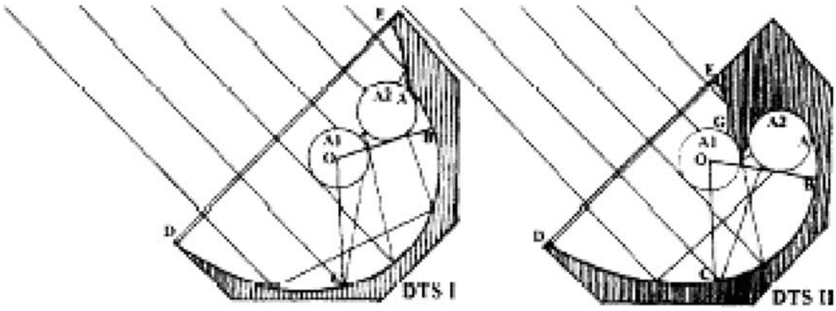

Fig. 10. Cross sections of double vessel configurations investigated by Tripanagnostopoulos et al. [27].

difference in the heat retention between the vessels in the partially exposed design, with the final tank retaining nearly 35% of the collected thermal energy over the non-collection period. A follow up investigation by Tripanagnostopoulos et al. [28] that compared the performance of double vessel systems with single vessel systems, concluded that double vessel systems utilising asymmetric CPC reflectors performed as well as single vessel symmetric CPC systems, although due to the larger exposed area, the double vessel systems had a higher measured heat loss coefficient. Under most conditions a 5 °C temperature difference was maintained between the upper and lower vessels, ensuring a draw-off temperature of over 40 °C under favourable weather conditions from the upper storage vessel.

Single and double vessel ICSSWH configurations utilising a concentrating collector were investigated by Kalogirou [17,18]. The modified double vessel unit consisted of two vessels mounted horizontally at the focal point of a symmetrical CPC reflector, as shown in Fig. 11. Cold water entered through the smaller upper vessel and was drawn out from the lower larger vessel. The results indicated that the double vessel system gave better heat retention and better draw-off characteristics but had the disadvantage of an 8% increase in capital cost.

The arrangement of vessel water connections can have a significant effect on the performance of ICSSWH systems with three or more vessels. Previous studies investigated the performance of triple vessel configurations, mounted vertically and linked in series, parallel and both series and parallel. Brooks [3] compared a system with vessels linked in parallel with a system with two outer vessels linked in parallel and the outlet taken from the central vessel in series. He found that the water drawn off in the morning from the centre vessel of the latter system was 64 °C, whilst that of the other system was 57 °C. Starr and Melzer [60] showed that a system with three vessels in series induced a temperature difference between the first vessel and the last vessel of 5 °C when the vessel temperatures were lowest in the early morning. The temperature difference was at a maximum at 5.6 °C around 5.00 p.m., under no draw-off conditions. As the outer vessels insulated the central vessel, water in the central tank of the system stayed warmer during night-time than that in the two outer vessels.

The amount of mixing of heated and unheated water within any vessel is dependant upon (i) cold water charge and hot water discharge cycles (ii) the size and location of inlets

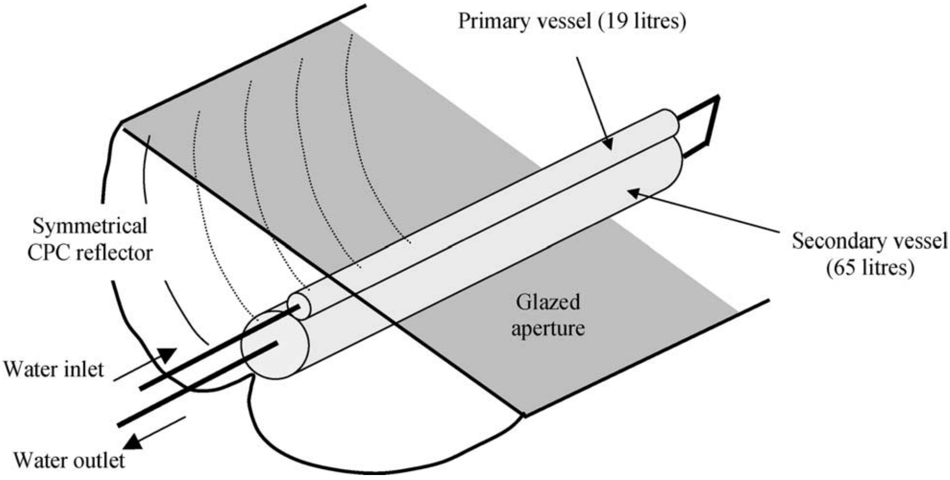

Fig. 11. A double vessel concentrating ICSSWH [18].

and outlets (iii) flow temperatures and velocities and (iv) vessel geometries [61–63]. In an attempt to further inhibit mixing in the ICSSWH vessel(s), inlet and outlet connections are usually fitted with manifolds. Fig. 12 details some of the different design configurations for an inlet pipe investigated by Carlsson [62]. Contrary to earlier studies, Carlsson [62] suggested that the use of circulation restriction inlet and outlet devices could improve the performance of high-flow systems compared to low-flow systems. The use of a manifold assembly has a twofold effect; collecting the maximum volume of the hot water in the upper portion of the vessel before drawing off cooler water and secondly restricting

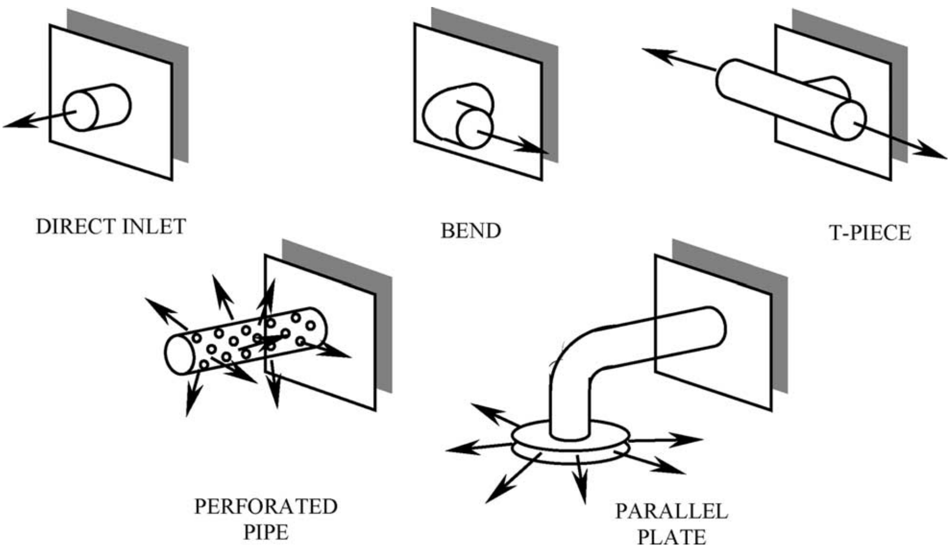

Fig. 12. Different design configurations for an inlet pipe [62].

the cold water inlet velocity so that cold inlet water is less likely to degrade stratification by mixing with warmer upper layers. Very little work to date has been conducted into the use of manifolds within ICSSWH systems, although the general principles that govern hot water storage tanks apply to ICS vessels.

2.1.3. Inclination and orientation of vessel(s)

The North–South orientation is more suited when a vessel is inclined vertically as it allows thermal stratification to develop in the water in the vessel. However, for concentrating systems, if a reflector is incorporated into a N–S aligned system, depending upon its acceptance angle, the duration of the diurnal collection period could be restricted. The benefit of using N–S orientated long-thin vertically mounted vessels only applies to systems located in relatively high latitudes. Most collector systems using a N–S alignment are tilted so that the plane of the aperture is normal to the incident insolation at the equinox (i.e. tilted at the same angle as the latitude). Systems in higher northern latitudes are often optimised for winter collection and are tilted 5–10° more than the angle of latitude [32]. This ensures that the collector presents a larger effective cross-sectional area to the incident solar radiation in winter when the sun is lower in the sky. The optimum inclination angle tends to the horizontal at latitudes approaching the equator. Horizontally mounted systems tend to be aligned in an East–West orientation. E–W orientated vessels mounted in concentrating systems are much less sensitive to reflector geometry which means that they can collect over the complete day. However, as cylindrical vessels mounted horizontally may allow the contained water to be only weakly thermally stratified, a reduced solar saving fraction (SSF) may ensue.

During the ICSSWH system 'revival' of the 1970s, there were many different designs built and tested with both N–S and E–W mounted vessels. One of the most innovative designs of this period was the 'Breadbox' solar water heater [9]. This design comprised two cylindrical vessels mounted horizontally, as shown in Fig. 13, so the collector was orientated E–W. This design facilitated the use of an insulated lid to cover the collector during the night to reduce heat losses. An interesting design [64], incorporated vessels in both orientations. This collector comprised one horizontal (E–W) inlet vessel and three vertical (N–S) vessels arranged so that the two vertical outer vessels were in parallel, feeding the middle output tank. Fig. 14 shows the schematic interconnection of the multi-vessel arrangement.

The water heater provided 100% hot water load from June to October in California, USA. Afternoon/evening water temperatures were adequate at 44–54 °C, but due to night-time cooling, morning water temperatures were sometimes lower than desired. From October to June the water heater was used as a pre-heater, feeding warm water to the auxiliary domestic hot water system. Details of insolation or ambient temperature were not provided for the test period.

Smyth et al. [23] investigated two ICSSWH systems with N–S mounted inclined ICS vessels, shown in Fig. 15. One system utilised a 1.0 m long vessel (57 l) that was fully enclosed within a concentrating collector and the other utilised a 1.5 m long vessel (85 l) that was partially enclosed within a concentrating collector. Both systems had identical collector set-ups and differed only by an additional one-third insulated upper storage volume in the partially enclosed system. Due to the greater storage capacity and lower

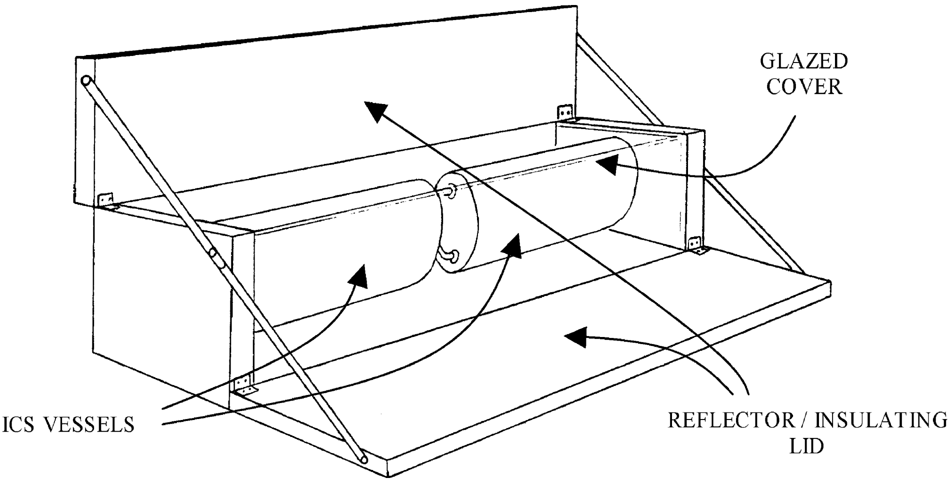

Fig. 13. A 'breadbox water heater' similar to Baer's [9] design.

average water storage temperatures the latter system exhibited a 13% increase in collection efficiency. The vertical mounting, greater aspect ratio and upper insulated portion of the vessel meant that the system also realised a higher solar saving fraction.

Tripanagnostopoulos and Souliotis [29] conducted a series of experimental investigations on the performance comparison of identical ICS solar systems with both

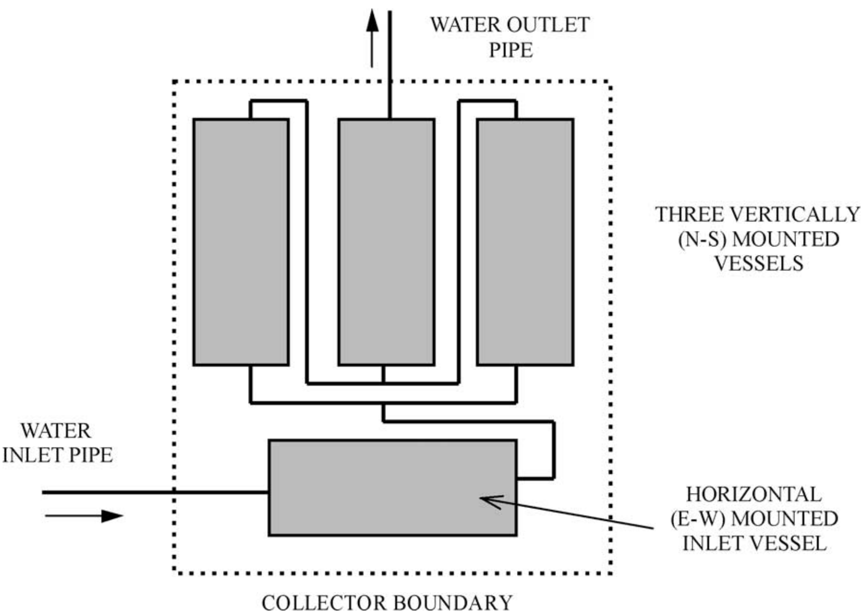

Fig. 14. Schematic detail showing the interconnection of Maeda et al.'s [64] multi-vessel ICSSWH.

Fig. 15. Detail of the two ICSSWH systems investigated by Smyth et al. [23].

horizontal (E–W) and vertical (N–S) mounted vessels. Their results indicated clearly that the vertical mounted vessel gave sufficient water temperature stratification, but it had a reduced mean daily efficiency and heat preservation compared to the horizontal mounted vessel. The better performance of the horizontal system is achieved with no extra cost.

2.1.4. Vessel materials

The vessel is the major component in an ICSSWH unit with the primary function to absorb solar radiation and transfer heat into the adjacent storage fluid. Early Japanese solar water heaters were initially constructed from wood, later systems were lined with plastic, today, however, copper, aluminium and stainless steel are most popular and more recently certain types of polymers pigmented black to absorb solar radiation are being used. Since metals are not good absorbers of solar radiation, a spectrally selective coating or paint is usually applied to absorber surfaces to provide good solar radiation collection.

Transfer of the absorbed solar energy to the storage fluid depends upon material thermal conductivity with materials such as copper and aluminium being very effective. For materials with a low thermal conductivity (less than 0.5 W/mK) such as polymers and rubber, the heat transfer path must be very short to ensure adequate heat transfer, thus a vessel's wall must be very thin. The use of butyl rubber as an ICSSWH vessel material was investigated as early as the 1960s [65]. In addition to heat transfer, the thermal conductivity of the vessel material can have a significant effect on thermal stratification within the vessel. Vertical conduction in the vessel wall, together with losses to ambient, induces convective currents that rapidly reduce thermal stratification. The degree of thermal conduction and corresponding convective motion depends upon the thickness and conductivity of the wall material [66–68].

Burns et al. [10] performed an experimental evaluation of an ICS solar 'breadbox' water heater to determine the stratification and performance characteristics in the moderate San Diego, California, USA climate. The collector consisted of an insulated rectangular wooden box containing a 250 l drum, painted black, where the aperture was covered by a single layer of glass. The unit was tested at a tilt angle of 40° from the horizontal. Burns et al. [10] concluded that thermal stratification is very important in the efficient operation of ICSSWH systems, however, he suggested that these systems should only be used for preheating, his tests were limited being conducted over an 8 day period at the end of April and thus cannot be used readily to predict the hot water production or optimum operating procedure for an ICSSWH system over the summer period. A heat retaining ICS vessel developed by Smyth et al. [20] consisted of an outer absorbing section made from aluminium and an inner perforated sleeve made from UPVC, detailed in Fig. 16. Reduced vessel wall conduction and thus convective motion and fluid mixing, improved thermal stratification in the inner store.

In addition to good absorption and thermal characteristics, the vessel material must be of sufficient strength and durability, lend itself to forming and fabrication and be of an appropriate cost. Copper and stainless steel have good structural strength. In inappropriate combinations, certain metals, are susceptible to corrosion, either externally or internally. Aluminium can suffer galvanic corrosion when connected to conventional copper pipework. Other low-cost metals such as mild steel and black iron have very high rates of oxidation [69].

Certain polymeric materials are resistant to degradation by water and other fluids; polyethylene, polypropylene and polyvinylchloride are used in domestic hot water

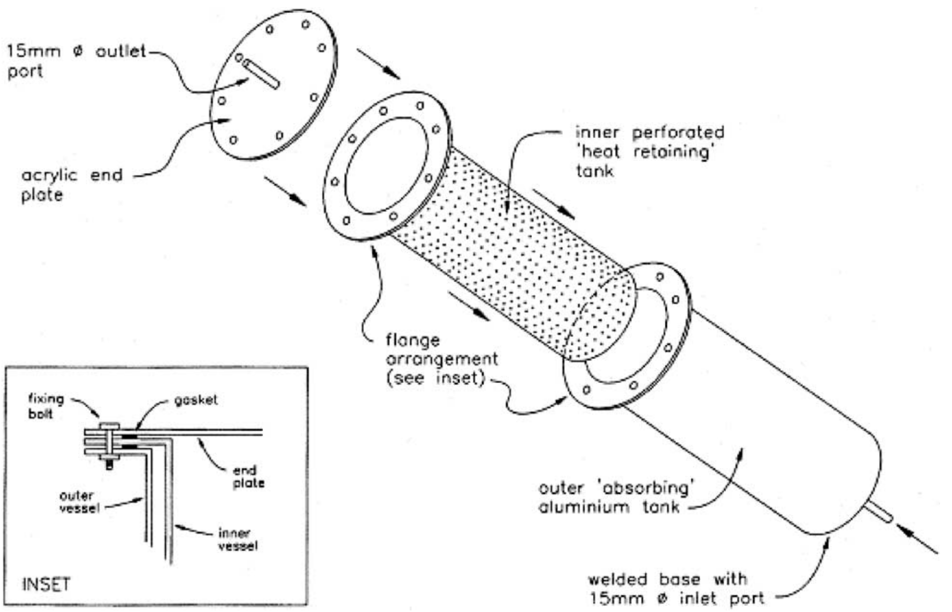

Fig. 16. Detail of the heat retaining ICS vessel design developed by Smyth et al. [20].

pipework. Polybutylene, chlorinated polyvinylchloride and nylon are also being employed as hot water pipe materials [69]. Whether these materials are suitable for use in ICS vessels depends upon their ability to resist ultra-violet degradation and withstand the temperatures reached at the vessel's absorbing surface. The long-term durability of polymeric materials in such conditions remains unproven.

2.1.5. Spectrally selective coatings

There are many different materials employed as ICS vessels, aluminium, stainless steel, copper and plastics such as polypropylene and acrylic. However, to enhance solar radiation absorption, an absorbent coating, and more specifically some form of spectrally selective absorber surface is usually required. Early passive solar enthusiasts in the USA understood this principle and most units were painted black. During the 1970s researchers and manufacturers started to take a specific interest in the surface treatment of the vessels. Stickney and Nagy [25] tested three types of ICSSWH units with and without a selective surface absorber. In all cases the collection efficiency improved, where a selective surface absorber was used. Burton and Zweig [70] compared systems with a selective absorber with those painted a dull black. The type of selective absorber used was a metallic nickel-chrome type with an absorptance of 0.97 and an emittance of 0.10. Although providing no specific details they found that the system with the selective surface coated absorber always produced the warmest water.

Several arrangements of different glazing materials combined with vessels with and without a selective absorber surface were compared by Bainbridge [71]. He found that a single-glazed unit with a selective absorber reached a higher temperature of 77 °C than a similar system painted black which reached only 68 °C by the late afternoon, in an ambient temperature of 21 °C. A series of experiments, conducted by Tiller and Wochatz [72], used selective surface paint with a solar absorptance of 0.94 and long-wave emittance of 0.45–0.60. These experiments were designed to compare the effectiveness of a glazing/selective absorber combination at reducing night-time heat loss with that of a moveable insulating lid/shutter. They found that the morning temperatures of the single-glazed shuttered design were 2.8 °C higher than those of the unshuttered selective absorber design (approximately 29.1 °C as opposed to 26.3 °C), but added that a selective absorber with lower emittance would have reduced this difference. In comparing total heat gain, the single-glazed shuttered design performed best. No details of ambient temperatures during the tests were provided.

A partially validated set of computer simulations were performed by Cummings and Clark [73] on selective absorber surfaces in conjunction with various glazing materials for all the climatic zones of the USA. In their computer model they used an absorptance of 0.95 and an emittance of 0.10 to simulate the selective absorber. They recommended that a single-glazed selective absorber design would give relatively high solar collection efficiencies for all climates, ranging from 42 to 51% with a corresponding solar saving fraction of 0.27–0.64, depending upon the test location. The solar collection efficiency is defined as the annual solar heat delivered to the load divided by the annual insolation on the net aperture plane. The solar savings fraction is defined as the heat input from the solar collector divided by the total thermal energy required by the load. In mild cloudy climates the collection efficiency was high, but the SSF low. The average increase in annual

delivered energy for the single-glazed selective absorber design over the single-glazed non-selective absorber design was 31%, with a range of 26–44%.

In a comparison of the performance of ICS solar water heaters using asymmetrical reflector designs with simple black paint $\alpha=0.92$ and $\varepsilon=0.9$) and a selective black coating $\alpha=0.95$ and $\varepsilon=0.11$), the systems with the selective coating had a significantly improved performance over the vessels covered with black paint [26]. However, the improvements reported were in part also due to an improvement in the reflector material employed. Fasulo et al. [14] examined the performance of an ICS system in Argentina using either selective absorbent coatings or matt black paint. They concluded that using a selective absorbent coating on the ICS vessel surface reduced night-time heat loss to 10 MJ/night compared to 13 MJ/night for a vessel with matt black paint surface finish.

2.2. Glazing

The primary function of glazing is to reduce convective losses by restricting air movement. Glazing also protects the absorber from the environment and particularly when glass with a low-iron content is used reduces radiative heat losses by reflecting thermal radiation emitted by the absorber. The most important property required of a glazing material is high transmittance of solar radiation, as any loss in transmittance will lead to a direct reduction in collection efficiency.

2.2.1. Vessel enclosure

In the 18th century the advent of cheaper and larger panes of glass, resulted in increased use of glass to trap heat from the sun in greenhouses and conservatories. The first patented commercial solar energy water heater [2], was simply a combination of de Saussure's 'solar box heater' [1] and a tank inside to hold the water. In their most basic form, the simple ICS water tanks first used in the USA were fully exposed to the elements and as a consequence wind movement across the aperture increased heat loss by convection and reduced the efficiency of conversion of solar energy to hot water.

A study that compared exposed vessels with enclosed vessels [3] found that a 108 l tank exposed in the sun on a calm day in July, produced enough hot water (at 39 °C) for 'two or three hot showers'. The presence of a transparent cover around the tank reduced convective losses thus improving the system efficiency. All subsequent ICSSWH designs incorporated some form of cover.

2.2.2. Glazing layers

The simple shallow trough water heater developed and tested by Tanishita [4] was sold in both single and double glazed versions. In the case of the single glazed unit, water vapour which evaporated from the water surface condensed on the inner side of the glass and reduced its transmittance and hence the overall performance of the collector. In the case of the double glazed design, the temperature of the inner glass rose above the dew point and no condensation took place. Baer [9] was the first to introduce an ICS solar water heater that had a double glazed glass aperture. McCracken [74] designed a similar simple ICS system with a double glazed glass aperture.

Bishop [75] reported on the testing of a large ICS water heater with two 170 l tanks incorporating six glazing layers, designed for use in freezing climates. The aperture cover comprised one sheet of low-iron glass and five sheets of high transmission polyester film and had an overall solar transmittance of 70% and an *R*-value of over $1\ m^2\ KW^{-1}$. Relative performance details provided indicated that a twin-tank system with $2.88\ m^2$ of glazing produced enough water at 50 °C in January for a family of four in the climate of Denver, CO, USA.

Studies by Fasulo et al. [76] investigated the nocturnal heat losses from a vertical cylindrical ICS vessel. The vessel was constructed from stainless steel with a capacity of 768 l and was covered with up to three concentric layers of polycarbonate multiwall sheet. Their experimental findings, based on a daily extraction volume of 210 l, showed that the output efficiency of the system varied between 26 and 31% for one polycarbonate layer and 28–36% for three layers. Fig. 17 details the design of a commercial ICSSWH that utilises a thermoplastic multi-glazed arrangement.

2.2.3. Glazing coatings

In the late 1970s and early 1980s, due to a greater awareness of the underlying physics, more attention was given to the effectiveness of appropriate glazing. New glazing materials and methods became readily available for use in solar water heating applications. Bainbridge [71] investigated the use of selective transmission films on glass apertures. The films are transparent to short wave radiation but reflect long wave (infrared) radiation, thus enhancing the greenhouse effect. He found that double glazing with a selective transmission film worked as well as moveable insulation in reducing night-time heat losses. However, infrared reflective coatings reduce the transmission of solar radiation [77] and it seems for most operating conditions the overall performance is

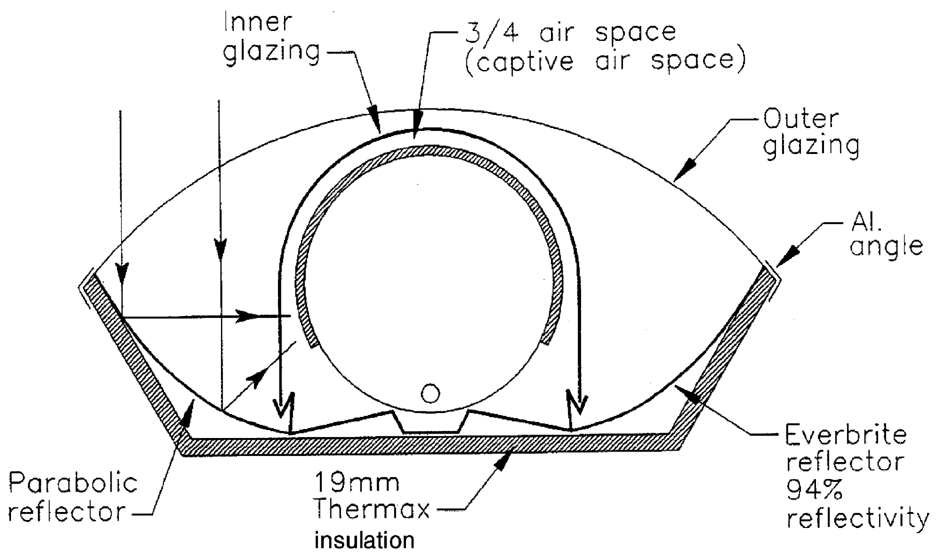

Fig. 17. Cross section detail of a thermoplastic multi-glazed ICSSWH manufactured by Aqua Sol, Barbados.

better with plain glazing than with glazing with an infra-red reflective film [78]. Another type of selective coating that can be used is anti-reflection coating. Most solar radiation transmission losses are due to reflection at the upper surface, which can be reduced by coating the glazing with a film of refractance intermediate between that of the air and the glazing material. However, the surface of the glazing is exposed to the atmosphere and subject to abrasion and dust accumulation and the expense of providing an anti-reflection coating is therefore not considered to be worthwhile [79]. Developments in AR coatings used in PV modules [80], however, may offer cost effective alternatives for solar thermal applications.

2.2.4. Storage volume/aperture area ratio

The lower the water storage volume per unit aperture area ratio (i.e. small volume, large glazing area), the higher temperatures and/or greater rate of heat gain per unit volume should be attained. However, it is practically and financially naive to consider an extreme ratio, as the amount of hot water delivered may be relatively small and the capital cost of the unit very high. Thus, as with most aspects of ICSSWH design, a compromise between cost and performance must be considered.

Investigations by Tiller and Wochatz [72], concluded that ICS systems with high storage volume/glazing ratios (102 l/m^2) operate better in warm weather than those of smaller ratios (51–69 l/m^2) unless hot water is used fairly continuously throughout the day. Other studies suggested a figure of 100 l/m^2 should be the maximum storage volume/glazing ratio [32]. Cummings and Clark [73] found that increasing the glazing area, increased the SSF but significantly decreased the efficiency. Tripanagnostopoulos and Yianoulis [26], Tripanagnostopoulos et al. [27,28], and Tripanagnostopoulos and Souliotis [29,30] have investigated experimentally various forms of ICSSWHs and have used storage volume/glazing ratios of 80–130 l/m^2.

2.3. Insulation

Thermal insulation of the storage vessel and associated casing was overlooked completely by early Japanese and US ICS solar water heater entrepreneurs. Subsequent designers have often employed less than the economically optimum thickness of insulation. Baer [9] was the first to investigate systematically the effects of varying the thickness of insulation, conducting a variety of experiments with simple ICS units. He added considerable insulation to the box and introduced a moveable insulated lid, the latter gave the water heater the appearance which led to the sobriquet 'breadbox'. These design modifications resulted in a significant improvement in the heat retaining properties of the ICS solar water heater.

2.3.1. Opaque insulation

Opaque insulation is used to minimise back heat loss from the ICSSWH. Where surfaces must be exposed to allow for solar collection, heat losses to ambient will ensue leading to the use of insulated moveable lids [9]. Golder [16] constructed and tested a low-cost integral solar water heater, designed for easy construction with limited workshop skills from readily available or recycled material. Based on Baer's [9] 'breadbox' design,

major modifications were aimed at reducing material costs. The water heater comprised a single cylindrical vessel, mounted horizontally within a cylindrical glazed envelope of flexible fibreglass sheeting. The flexible insulated cover, which reduced night-time heat loss is opened during the day and doubles as a reflector to increase the aperture catchment area. The necessity to remove and replace the insulated cover physically on a daily basis was not generally acceptable to practical users. This led to the development of automated moveable lid [9]. However, such open and close mechanisms require parasitic power and introduce components into the system with maintenance requirement and increase the potential for failure.

Smyth et al. [23] conducted a series of indoor comparisons on the performance of two ICSSWH systems with vertically mounted vessels with differing insulation configurations. The systems are shown in Fig. 18. One vessel was fully enclosed within a concentrating collector and thus fully exposed whilst the other had a vessel that was partially enclosed within a concentrating collector, with the upper 1/3 of the vessel fully insulated. Due to stratification of the water, the upper insulated portion increased thermal retention by nearly 23% and up to 37% in the upper storage portion of the vessel. Tripanagnostopoulos and Souliotis [30] conducted similar experiments on horizontally mounted systems, partially enclosing the vessels into the fabric of the collector.

2.3.2. Transparent insulation

Transparent insulating materials (TIM) minimise heat loss through the aperture without the daily need for covering and removal of insulating lids. However, early attempts to use these materials led to decreases in system efficiency due to their poor solar transmittance. McCracken [74] wrapped ICS tanks in insulation with a transmittance of 0.85 to prevent night-time losses, but this had the disadvantage of decreasing the daytime collection efficiency by about 20%. More recently the use of transparent insulating glazing materials, such as organic-based transparent foams, honeycomb or capillary structures, or inorganic glass foams such as silica aerogel has led to greater collection performances [81–83].

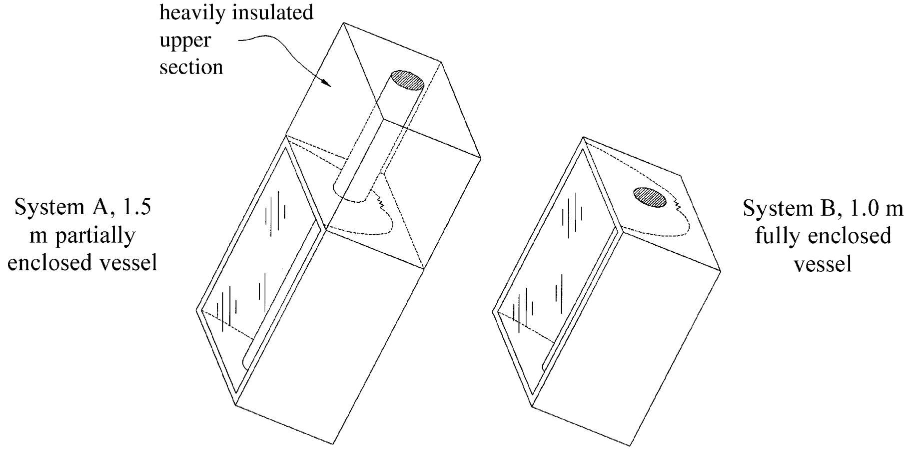

Fig. 18. Detail of fully exposed and partially enclosed ICS vessels [23].

Goetzberger et al. [81] performed research on transparent insulation materials in thermal storage systems and carried out subsequent investigations involving ICS systems and insulated transparent glazing. Rommel [40] developed a model that simulated the behaviour of a 'tank in a glazed box' using transparent insulation. The model was based upon a flat box configuration. The collector was insulated on the front side with a transparent insulating material and on the other sides with opaque thermal insulation. Protection against overheating was provided by an automatically-operated roller blind. A simulation indicated for a Northern European climate an optimum water layer depth of 100 mm. For a depth less than 100 mm, there is a possibility of freezing, whilst greater than 100 mm leads to decreased overall efficiencies. From simulations it was concluded that an increase of the transmittance-absorptance product by 0.1 resulted in an increase of the SSF by 6%.

Schmidt et al. [84] developed several ICS systems consisting of a pressure-resistant single tube absorber mounted in an involute reflector and covered by highly transparent insulation material. The collectors were located in Freliburg, Germany, with a hot water demand of 160 l/day. An ICS system similar to the unit illustrated in (Fig. 19) gave an annual solar saving factor of 58% and had an overall annual efficiency of 28%. It was concluded that given the local climatic conditions, there was no risk of freezing. The system was improved and simulated at a later date by Schmidt and Goetzberger [19] to determine the effect of various parameters on performance Fig. 19. Measurement and simulation indicated that the ICS performance was almost constant for transparent insulation with a thickness of about 50–150 mm (polycarbonate honeycomb structure). It was predicted for Northern European climates that the risk of freezing only occurs for ICS

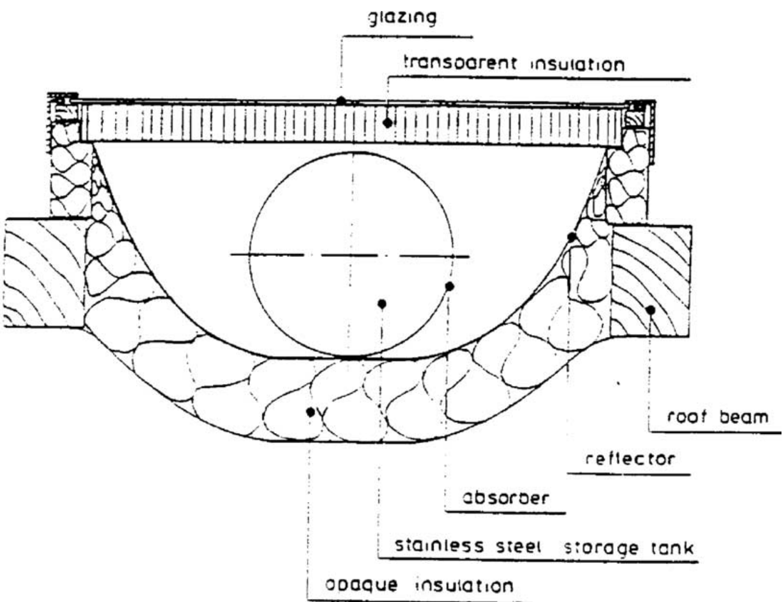

Fig. 19. Cross section of a collector/storage system with a TIM [19].

systems with a specific collector volume lower than about 70 l/m^2 (damage due to freezing only occurs if more than 20% of the ICS water content is frozen).

Studies of an ICS unit by Rommel and Wagner [41] concluded that transparent insulation materials produce good performance in simple ICS systems. However, thermal stagnation (temperatures in excess of 80 °C) within the collector compromised the integrity of the polycarbonate honeycomb glazing. Due to this a transparent insulating material made from glass capillaries, that can withstand temperatures of 261 °C, was recommended.

The performance of collector cum storage solar water heaters with and without transparent insulation material has been compared [85]. Two identical units were tested, one with TIM and the other without. The TIM covered system had a total heat loss factor of 1.03 W/m^2 K whilst the glass only system was 7.06 W/m^2 K. The TIM glazed system yielded hot water at temperatures 8.5–9.5 °C higher than the glazed system the next morning. The storage efficiency of such solar water heaters was 39.8% with TIM glazing compared to 15.1% without the TIM. In a series of comparative studies on the effect of different transparent insulation materials and different absorber TIM configurations for an ICSSWH [42], it was concluded that TIM cover systems based on the absorber perpendicular configuration (transparent honeycomb (cellular structure) immersed in an air layer) exhibit superior solar collection-storage efficiencies over corresponding absorber parallel configurations (multiple covers of glass/plastic films placed parallel to absorber).

2.4. Reflectors

To increase the solar radiation incident on the absorber surface over that incident at the collector aperture, reflectors are employed in solar water heating systems. Reflecting concentrator designs for low to medium concentrations can be flat or curved, line-axis or line-focus (circular, parabolic or compound parabolic) reflectors, symmetrical or asymmetrical. Reflectors are used to obtain higher temperatures on the absorbing surface by increasing the ratio of incident energy to heat loss temperatures increasing with higher concentration ratios. In concentrating systems, the absorbing surface area is reduced relative to that of the aperture leading to a reduction in the overall heat loss from the system, hence improving thermal efficiency.

Following the renewed interest in solar water heaters in the 1970s, there followed a period of increased development of ICS solar water heater designs that utilised internal reflectors. Davis [11] built a symmetric cusp reflector ICSSWH system designed for the cold climate of Colorado, USA and claimed a collection efficiency of 72%. An inverted ICS solar water heater designed by Stickney and Nagy [25] consisted of a slender glass lined tank enclosed in insulation with a double glazed aperture facing downward to collect the reflected solar radiation from the parabolic reflector. This could only collect mostly direct radiation and for only 3 h. However, this was enough to produce afternoon water temperatures of 40–55 °C with good night-time heat retention. A Tunisian design [86] that also used the inverted ICS feature for good heat retention had no need for daily adjustment. The unit consisted of a rectangular water vessel, insulated on the top and sides, and had a corrugated plastic aperture facing down towards a moveable reflector profile. It was capable of supplying hot water at 75 °C in 2 h in typical insolation conditions and retained enough

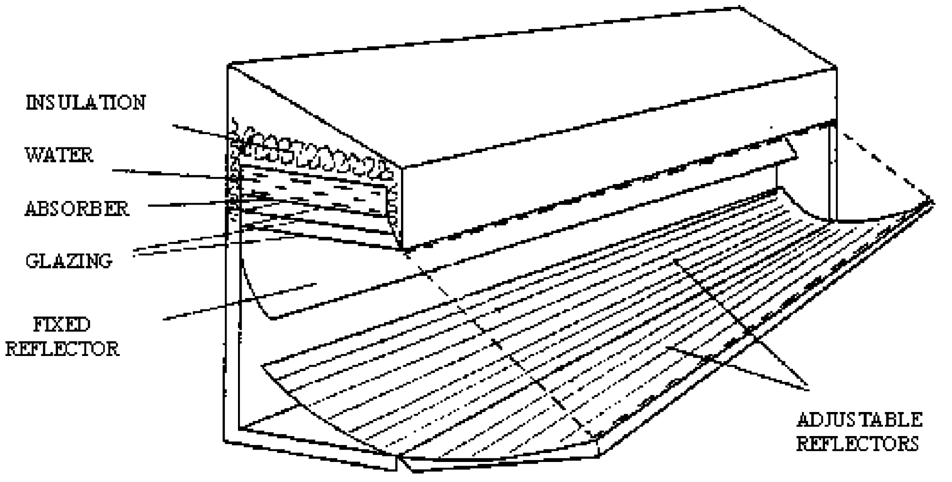

Fig. 20. An inverted 'shallow' solar pond ICSSWH [87].

heat during the night to supply water at 67 °C the following morning. Heeschen [87] developed a similar design, shown in Fig. 20. On clear winter days (ambient temperatures on average −5°C) the heater delivered around 15 MJ of net collected energy from the 72 l store. Even on poor days, the heater still delivered around 18 l of water at 50 °C.

Stickney and Aaboe [24] reported on a design known as a 'Snail Batch Water Heater' because of the shape of the fixed reflector profile. Fig. 21 illustrates the system's design. The design utilised the basic features of Heeschen's [87] design, but also had the added

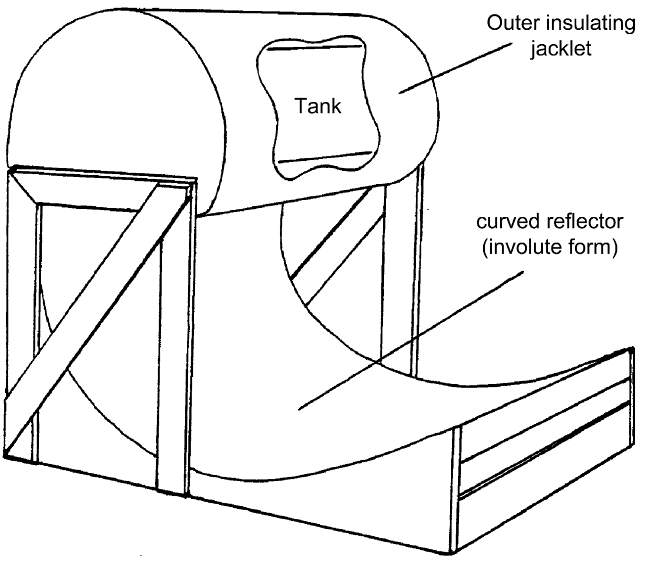

Fig. 21. The 'snail' type batch solar water heater [24].

advantage of being able to collect diffuse as well as direct insolation. Schmidt and Goetzberger [19] compared the performance of two ICS prototypes with symmetrical involute reflectors and TIMs. No data is available on the performance of the systems based on these reflector designs.

Tripanagnostopoulos and Yianoulis [26] developed ICS solar water heaters that incorporated asymmetrical reflector designs that are designed to minimise thermal losses by creating a stagnant air layer around the absorber/storage vessel to suppress convective heat transfer. They suggest that a truncated CPC for a stationary collector should have a concentration ratio of 1.5. Compared to symmetrical systems of a similar construction, the asymmetrical designs resulted in a better overall efficiency for water heating through reduced thermal losses although due to an increase in the average number of reflections reduced optical efficiency.

A more detailed study by Tripanagnostopoulos et al. [27,88] broadened the investigation to include double vessel configurations and different reflector materials (polished stainless steel sheet and aluminised mylar). Fig. 10 details the different double vessel configurations investigated. In addition, comparisons were made with a typical flat plate thermosiphonic unit. The partially-enclosed single and double vessel asymmetrical configurations using a mylar reflector exhibited the best mean daily collection efficiencies, even better than the flat plate unit. Systems using the stainless steel reflector had lowest mean daily collection efficiencies. All ICSSWHs had a higher heat loss coefficient than the flat plate unit and due to the larger exposed area all double vessel arrangements had a higher heat loss coefficient in comparison to the single vessel units. The experimental investigation also observed a small contribution to reduced night-time heat loss from the aluminised mylar reflector systems due to the lower thermal radiation losses from the metallic reflector surface. More detailed studies on the aspects of asymmetric CPC reflector systems followed [30]. Fig. 22 illustrates some of the ICSSWH designs investigated.

Smyth et al. (2001b) detail the annual performance of two ICSSWHs with ICS vessels mounted vertically at the focal point of a truncated McIntire [89] modified concentrating

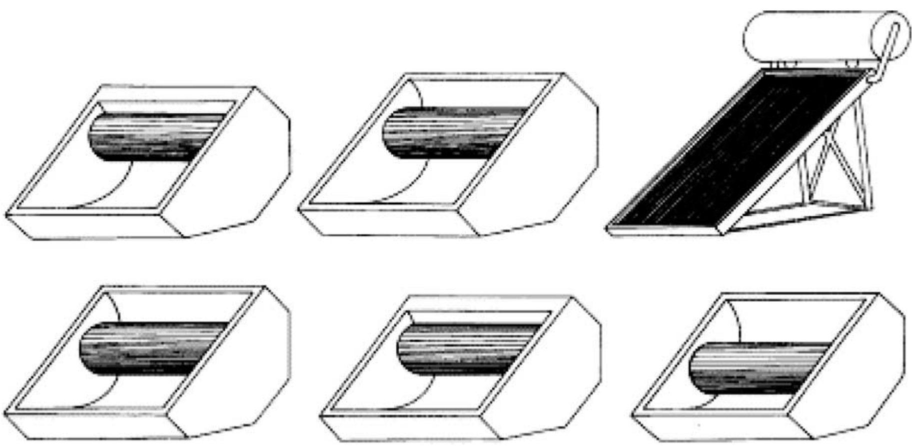

Fig. 22. Front-side view of the systems investigated by Tripanagnostopoulos and Souliotis [30].

cusp reflector with a concentration ratio of 1.15. One system utilised a 1.5 m long vessel that was enclosed partially within the concentrating collector (system A) and the other utilised a 1.0 m long vessel that was enclosed fully within the concentrating collector (system B). Both systems were tested under identical conditions for a period of 1 year in the Northern Ireland climate. System A outperformed system B in terms of solar energy collection over the year with system A achieving 45.5% and system B 43.7%. However, when the usefulness of the solar energy collected in terms of hot water stored is analysed, system B gives a slightly improved performance for the Northern Irish climate. Values of $\Delta T/I_{\mathrm{ave}}$ (where ΔT is the difference between the average vessel water temperature of the heating period and the average ambient temperature over the same period and I_{ave} is the average insolation on the collector aperture) between 0.025 and 0.06 represent the most frequent range of operation for domestic hot water units [26]. In this range, operational collection efficiencies for system A and B were 40–55% and 43–56%, respectively.

Work conducted by Smyth et al. [43] investigated the performance of an inverted absorber ICSSWH mounted in the tertiary cavity of a compound parabolic concentrator with a secondary cylindrical reflector under solar simulated conditions. The work examined the performance of the system with several types of transparent baffles at different locations within the collector cavity. The basic collector without baffles attained a collection efficiency of 56.1%. Using a 100 mm deep glass baffle at the upper exit of the CPC increased collection efficiency to 59.3%.

2.5. Evacuation between cover and vessel

As the operating temperature of a solar collector increases, increased thermal losses reduce the collector efficiency. Evacuation of the space between the glazing and the absorber surface is used to increase the collection efficiency of various commercial ICSSWHs. An experimental study of an evacuated-tube ICSSWH was conducted using an indoor solar simulator by Mason and Davidson [90]. The purpose of the study was to characterise experimentally radiation induced stratification and mixing during hot water draw-off and to evaluate a TRNSYS [91] ICSSWH system model applied to the evacuated-tube design. There was limited agreement between the model and different operating conditions and it was concluded that future models should account for radiation-induced stratification as well as heat conduction in the ICSSWH during draw-off. Menon [92] developed and validated a model to evaluate the performance of integral collector storage evacuated tubular collector DHW systems. Hongchuan and Guangming [93] investigated the absorbed energy factor changing with the incident angle at different centre-to-centre distances of integral collector storage evacuated tube (ICSET) systems with full-circular and semi-circular selective coated absorbers. The results showed that the annual absorbed energy of ICSET with full-circular coated absorber is 9% higher than with semi-circular coated absorber.

2.6. Baffles in heat store

Baffles have been introduced successfully into ICSSWH designs, both within the vessel [36] and the collection aperture. Taylor [88] filed a US patent describing a simple

rectangular solar water heater that incorporated a baffle arrangement that separated the vessel into two connected volumes, an outer collecting volume and inner storage volume. No values of performance are presented. Shurcliff [38] describes the operation of a wall mounted integral solar water heater that incorporates a baffle. Sokolov and Vaxman [49] first conducted numerical and experimental studies of baffle plates within triangular and rectangular ICSSWH systems. Kaushik et al. [94] conducted a detailed evaluation of a triangular ICS systems with a baffle plate similar to above (see Fig. 23). The inclusion of the plate had a significant effect on the systems performance, especially during non-collection periods. The study indicated that the thickness and material of the baffle had little impact on the system performance.

Mohamad [95] built on previous developments in triangular ICS systems with baffle plates and introduced a simple thermal diode to prevent reverse circulation at night-time, as shown in Fig. 24. The thermal diode consists of a light weight plastic 'gate' that allows one-way flow only located at the entry to the baffle at the bottom of the vessel. Mohamad [95] presents vessel storage efficiencies of 68.6 and 53.3% for the vessel with and without the diode, respectively.

A 'high speed cylindrical' solar water heater developed by Vincze [31] was one of the earliest modern commercial ICS systems to incorporate an inner baffle-cum-baffle arrangement. The vessel consisted of two concentric cylinders, one inside the other to produce a narrow annular passage. Solar radiation falling on the black outer surface heats the water in the narrow annular space, causing it to rise whilst cooler water inside the vessel descends, establishing a natural thermosyphon circulation. Adding reflectors just

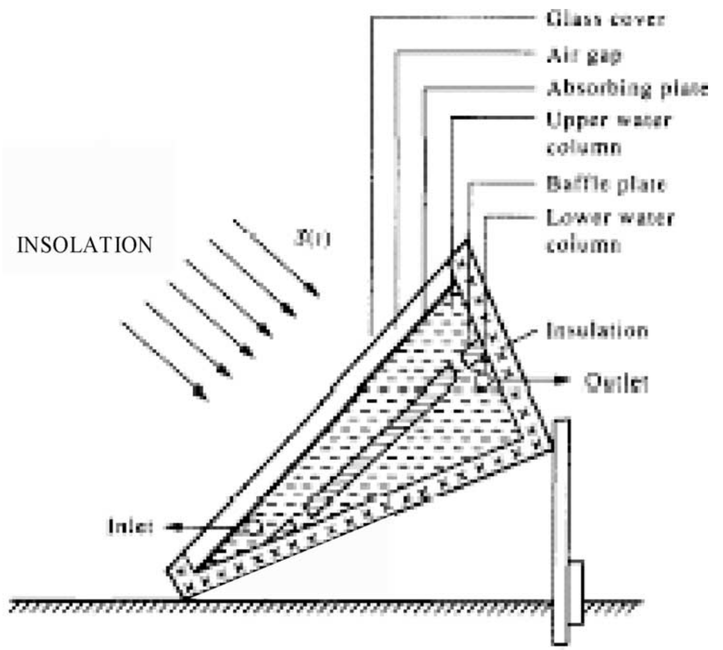

Fig. 23. Schematic detail of the triangular built-in-storage solar water heater [94].

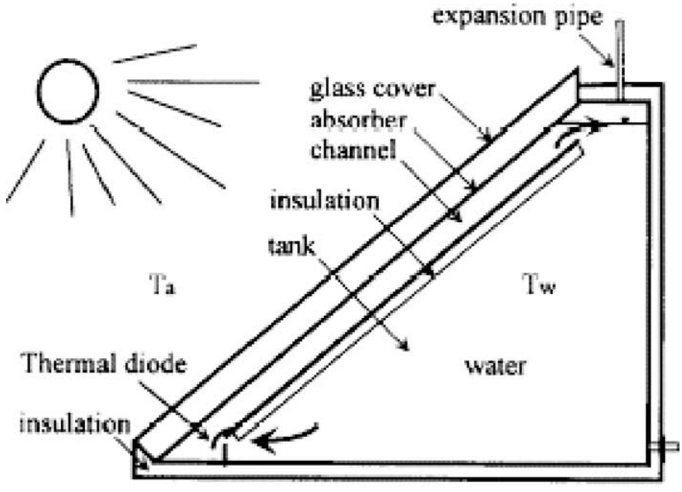

Fig. 24. Schematic detail of the integrated solar collector-storage tank [95].

below the cylinders enhances collection. A comparison of Vincze's unit with a flat plate collector showed that temperatures attained in the same period of time were 71 and 49 °C, respectively. Smyth et al. [20] developed a heat retaining ICS vessel consisting of an outer absorbing section and a perforated inner sleeve manufactured from a material with a low thermal mass.

The operating principle is illustrated in Fig. 25. During energy collection periods, thermal buoyancy leads to natural circulation within the vessel(s). Water adjacent to the exterior surface is heated, rises, and passes through the perforated inner sleeve into the inner store, leading to a high degree of thermal stratification within the inner store. The perforations of the sleeve were designed to aid flow from the outer channel to the inner store during collection periods but to reduce flow, through increased resistance, during non-collection periods. Further experimental investigation [21–23] of the vessel installed within a concentrating collector have shown the benefits of using the heat retaining vessel in terms of increased collection during collection periods and improved heat retention during non-collection periods.

The introduction of convection suppression devices in concentrating collectors have been well documented [13,96]. Eames and Norton [97] investigated the thermal and optical consequences of using transparent baffles in compound parabolic concentrating solar energy collector cavities and concluded that baffles can be employed to give reduced collector heat losses without a significant reduction in optical efficiency. An experimental investigation into the performance of an inverted absorber ICSSWH mounted in the tertiary cavity of a compound parabolic concentrator with a secondary cylindrical reflector using several types of transparent baffles at different locations within the collector cavity was conducted by Smyth et al. [43] for radiation incident perpendicular to the aperture. Fig. 26 illustrates the inverted absorber ICSSWH investigated. They concluded that increasing collector performance by using transparent baffles in the collector cavity is

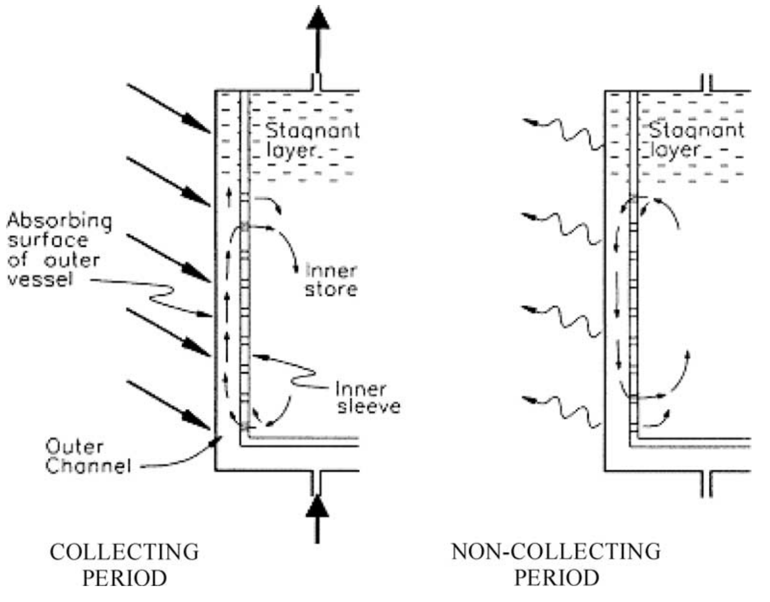

Fig. 25. Operating principle of the heat retaining ICS vessel design [20].

a balance between the thermal and optical interactions of the system. Utilising full baffles or baffles located at the wrong position introduce unnecessary surfaces at which superfluous reflections and absorption of incident radiation occurs, thus cancelling any thermal benefits of reduced fluid motion. Using transparent baffles that extend part of

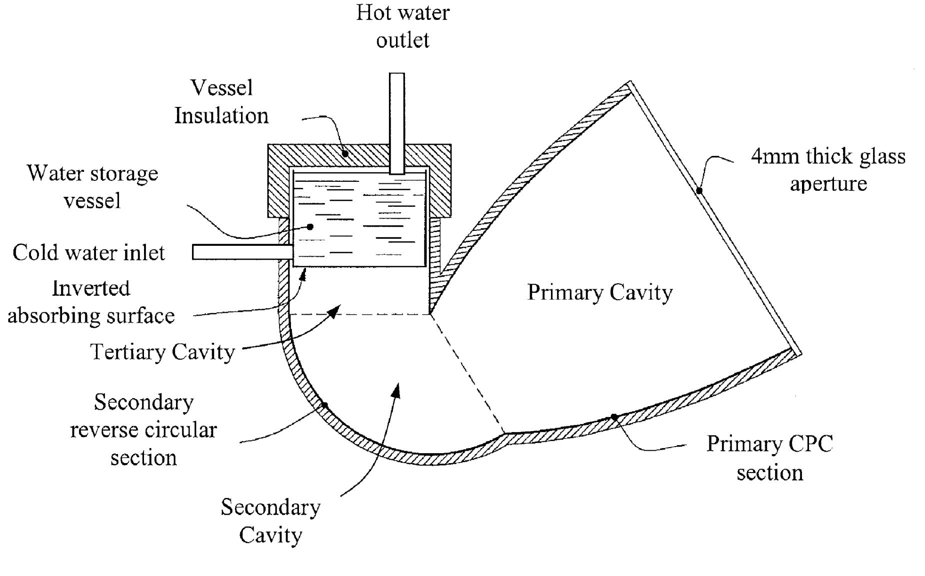

Fig. 26. Detail of the inverted absorber ICSSWH [43].

the way across the entry to the secondary cavity reduces convective heat transfer from the absorber to ambient without significantly reducing the optical efficiency.

2.7. Inclusion of phase change materials

The use of a salt-hydrate phase change material (PCM) in an ICS solar energy collector was investigated experimentally by Rabin et al. [98]. A one-dimensional model was also developed to investigate the charging process of the system. They concluded that this type of system can yield a collection performance of approximately 66% during the winter in Beer-Sheva, Israel, but that the use of such a system is likely to be limited to special applications, such as space and soil heating greenhouses in arid areas, during winter.

De Beijer [12] describes the development of a novel ICSSWH system that incorporates two cylindrical vessels, an outer absorbing vessel and an inner storage vessel. Fig. 27 shows a side detail of the novel ICSSWH system. The space between the two vessels contains a small pool of water, which when heated evaporates and consequently condenses on the surface of the colder surface of the inner vessel, thus transferring thermal energy to the store. The system has a predicted yearly collection of 1170 kW h in the Dutch climate.

2.8. Icsswh performance characterisation

Experimental methods of testing solar water heaters allow users to make product comparisons through common performance indices. In USA, the ASHRAE Standard-95

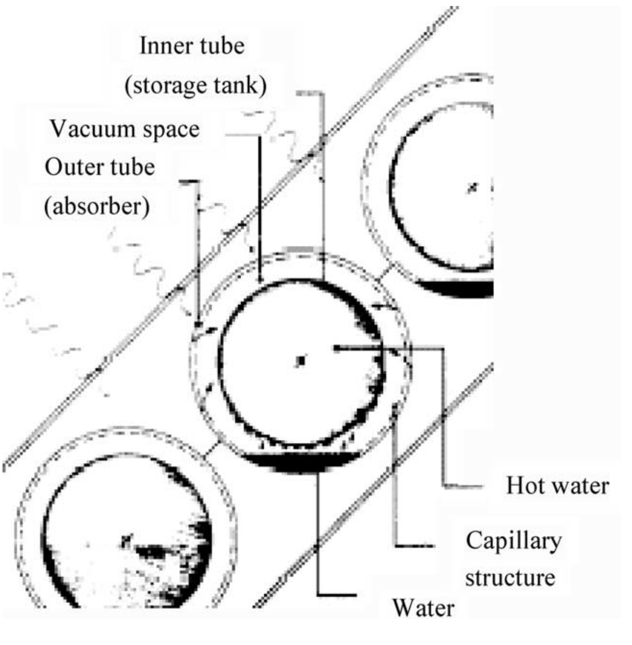

Fig. 27. Side detail of the novel ICSSWH system utilising a partial vacuum and phase change for both heat transfer and insulation [12].

[99] is an industry benchmark that is used as a short-term performance testing method. In Europe, the European Solar Collector and Systems Testing Group [100] have developed a standard testing procedure for all forms of solar water heaters used in the European Community. Although both test methods make provision for the testing of ICSSWH systems, the ASHRAE Standard-95 [99] does not provide prediction of long-term performance. Bainbridge [71] and Thomas [101] have both developed test procedures, based on the ASHRAE Standard-95 [99], for ICSSWH systems to provide long-term performance data.

Boussemaere and Bougard [102], as part of the CSTG project, experimentally investigated testing procedures for ICSSWHs. The study looked at long-term daily, short-term daily and component tests. The study concluded that an input/output approach used for long-term daily evaluation must use characterisation data collected from the short-term daily test procedure. Tests on component parts can be used in computer simulation programs to predict the long-term performance. An experimental methodology employed to determine ICSSWH system collection performance was developed by Tripanagnostopoulos and Yianoulis [26]. The test procedure is a combination of test methods proposed by the European Solar Collector and Systems Testing Group [100] and gives a realistic ICSSWH performance representation which allows direct comparison with other experimentally investigated ICSSWHs. The collection efficiency is superficially similar to the Hottel-Whillier-Bliss equation for distributed type solar collectors [103,104], but applies to diurnal system performance. Plots of collection efficiency are made against values of $\Delta T/I_{ave}$, where ΔT is the difference between the average vessel water temperature of the heating period minus the average ambient temperature over the same period and I_{ave} is the average insolation on the collector aperture. However, direct comparison of measured system performances is quite simple, predicting the performance of an ICSSWH at another location or different installation set-up is more challenging.

In a follow-up study based on previous experimental investigations, Boussemaere [105] reported on the simulation of an ICSSWH. The study did not seek to replace experimental testing with computer simulation but rather evaluate the effect the test procedure had on the system characterisation. The first study to propose and use computer simulation to predict the performance of ICSSWHs was conducted by Garg et al. [34]. The work was rudimentary and involved a single node system, however, since this early pioneering study, much work has been conducted to predict the performance of ICSSWHs.

Stickney and Aaboe [24] developed a simple method that allowed direct comparison of ICSSWHs. The method required the calculation or measurement of system variables, such as thermal efficiency of collection and tank heat loss coefficient, to produce one of four performance indices. The performance indicator could then be used by a consumer or designer to compare and select an ICSSWH for their requirements. Faiman [106] reported on a standard method to determine the efficiency of ICSSWHs though the use of a maximum useful efficiency (MUE). Weller et al. [107] conducted work on an experimental program to predict the energy losses and heat storage delivery efficiency of a commercial integral passive solar water heater. The work was based on the earlier work by Cummings and Clark [73] on the performance prediction of an ICSSWH in 10 US climates. Weller et al. [107] showed that the energy losses through the aperture could be represented using a simple lumped cooling model. Burns et al. [10] reported on a study to

Table 1
System parameters for generic collector employed in performance prediction [114]

$A_c = 0.46\ m^2$	$(mC)_n = 2.5\ W\ h\ K^{-1}$	ϕ as required
$A_b = 1.8\ m^2$	$(mC)_p = 0.75\ W\ h\ K^{-1}$	$\beta \sim \phi + 10°$
$h_o = 278.28\ W\ m^{-2}\ L^{-1}$	$(mC)_t = 1.25\ W\ h\ K^{-1}$	$\gamma = 0°$
$U_B = 0.38\ W\ m^{-2}\ K^{-1}$	$(mC)_w = 113.6\ W\ h\ K^{-1}$	$\alpha = 0.98$
$T_{wi} = 10\ °C$	$h_w = 10\ W\ m^{-1}\ K^{-1}$	$\varepsilon = 0.07$

develop an analytical model to predict the performance of a stratified ICSSWH. Good agreement between theoretical and experimental results were reported although the work concluded that ICSSWHs are best suited to water pre-heating roles.

Thermal performance simulation for ICSSWH have been developed [91,108–110]. These [91,110] and other techniques [111–113] have been employed to predict the solar savings fraction from the use of an ICSSWH with a particular specification subject to a specified pattern of withdrawal of heated water under given weather conditions. Fanney and Klein [76] compared the experimental performance of an ICSSWH over a one year period with the performance predictions of the method used by Zollner et al. [91]. They concluded that the agreement between the experimental results and the predicted performance was excellent. Comparison of daily solar savings fraction for the ICSSWH (system parameters detailed in Table 1) for five European locations has been summarised in the form of a nomogram given in Fig. 28 [114]. Garg et al. [115] also developed

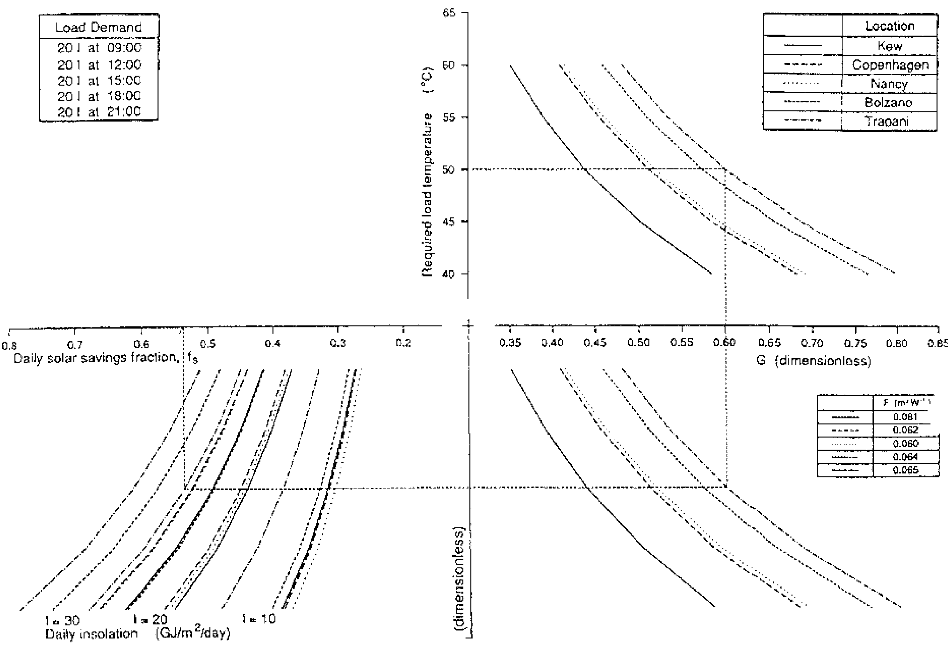

Fig. 28. Representative nomogram for generic collector at five European locations [114].

a nomogram for performance prediction of ICSSWHs, building on analysis carried out by Hobson and Norton [116].

3. Conclusion

Integral solar water heating systems generally resist freezing in most climates and have generally a lower cost. Through innovation the performance of ICSSWHs can also be demonstrated to be in some cases on a par with distributed solar water heating systems, if not better when cost versus useful energy gain is considered. However, the ICSSWH remains less common than distributed pumped and thermosyphon solar water heating systems.

To date, very little work has given adequate consideration to the integration of ICS solar water heaters, specifically within domestic buildings. Some work [12] has looked at novel solar water heater mounting locations, but given the advances in ICSSWH development, it would be worthwhile for future studies to investigate the trade-off in system performance with reduced installation costs, better services integration and improved aesthetic appearance.

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